

THE $b \rightarrow s + \gamma$ DECAY IN SUPERGRAVITY

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The $b \rightarrow s + \gamma$ decay is a powerful tool for testing models of new physics because the new physics diagrams enter in the same loop order as the Standard Model ones. The current experimental and theoretical status of this decay is reviewed. Predictions based on the minimal supergravity model (MSGM) in the leading order (LO) are discussed. It is shown that results are sensitive to the value of m_t and α_G . The current experimental value for the $b \rightarrow s + \gamma$ rate already very likely eliminates part of the SUSY parameter space when both m_o and $m_{\tilde{g}}$ are small and when A_t and μ have the same sign. Dark matter detection rates for \tilde{Z}_1 cold dark matter for $\mu < 0$ are only minimally affected by the current data, as are proton decay predictions for models consistent with current proton lifetime and \tilde{Z}_1 relic density bounds. [†Invited talk at “Physics From Planck Scale to Electroweak Scale”, Warsaw, Sept. 21-24, 1994].

1. Introduction

It is generally expected that the TeV energy domain will bring forth an array of new physics. There are many speculations as to what form this new physics will take: supersymmetry, technicolor, compositeness, additional W and Z bosons, etc. Unfortunately, most of the precision LEP measurements are not very sensitive to new physics as the Standard Model contributions enter at the tree level, while possible new physics contributions begin at the loop level. Thus the most one might hope for in these measurements is a few percent correction from new physics.

The recently discovered decay by CLEO of $b \rightarrow s + \gamma$ is an exception to this as this process is sensitive to new physics and is observable for several reasons:

- Being a FCNC process, it begins at the loop level so that Standard Model loops and new physics loops enter at the same level. Thus there can be large new physics corrections.
- It is of size $G_F^2 \alpha$, where G_F is the Fermi constant (rather than $G_F^2 \alpha^2$ as is usual for FCNC processes)
- QCD corrections are large and enhance the rate by a factor ≈ 3 .

In spite of this, it is difficult at this time to make detailed statements concerning how well theory and experiment agree. First the experimental errors are still quite large. Further, the large QCD corrections mean that next to leading order (NLO) QCD effects are important and these are difficult to do. Thus theoretical errors are currently also quite large. One can, however, still learn interesting things at this level of knowledge, and as experiment and theory get refined, more precise statements will become available.

2. $b \rightarrow s + \gamma$ Decay

The $b \rightarrow s + \gamma$ branching ratio measured by CLEO is¹

$$BR(B \rightarrow X_s \gamma) = (2.32 \pm 0.5 \pm 0.29 \pm 0.32) \times 10^{-4} \quad (1)$$

where the first error is statistical, and the last two are systematic. If one combined errors in quadrature one obtains $BR(B \rightarrow X_s \gamma) \cong (2.32 \pm 0.66) \times 10^{-4}$ which has an error of about 30%. In the spectator approximation one may relate the B meson decays to the b quark decays:

$$\frac{BR(B \rightarrow X_s \gamma)}{BR(B \rightarrow X_c e \bar{\nu}_e)} \cong \frac{\Gamma(b \rightarrow s + \gamma)}{\Gamma(b \rightarrow c + e + \bar{\nu}_e)} \equiv R \quad (2)$$

where $BR(B \rightarrow X_c e \bar{\nu}_e) = (10.7 \pm 0.5)\%$. [The spectator model has corrections that begin at $O(1/m_b^2)$.]

At the electroweak scale $\mu = O(M_W)$, the elementary diagrams involve the W-t-quark loop for the Standard Model plus additional loops (H^- -t-quark, $\tilde{W}^- - \tilde{t}$ -squark) for the supersymmetric generalization (Fig. 1). Thus at $\mu \approx M_W$ the interaction can

Fig. 1 Elementary diagrams for $b \rightarrow s + \gamma$ decay at scale $\mu \approx M_W$. Only the third generation quark and squark contribute significantly.

be described by an effective Hamiltonian²

$$H_{eff} = V_{tb} V_{ts}^* \frac{G_F}{\sqrt{2}} C_7(M_W) Q_7 \quad (3)$$

where $Q_7 = (e/24\pi^2)m_b\bar{s}_L\sigma^{\mu\nu}b_RF_{\mu\nu}$. Here $F_{\mu\nu}$ is the electromagnetic field strength and m_b is the b quark mass. However, the decay occurs at $\mu \approx m_b$, and one must use the renormalization group equations (RGE) to go from M_W to m_b . This produces operator mixing with the color transition magnetic moment operator $Q_8 = (g_3/16\pi^2)m_b\bar{s}_R\sigma^{\mu\nu}T^Ab_LG_{\mu\nu}^A$ where T^A and $G_{\mu\nu}^A$ are the gluon generator and field strength) and with six 4-quark operators $Q_1\dots Q_6$. The ratio of Eq. (2) at $\mu = m_b$ becomes then

$$R = \left|\frac{V_{ts}^*V_{tb}}{V_{cb}}\right|^2 \frac{6\alpha}{\pi I(z)} \frac{|C_7^{eff}(m_b)|^2}{\left[1 - \frac{2}{3\pi} \frac{\alpha_3(m_b)}{\zeta} f(z)\right]} \quad (4)$$

where $z = m_c/m_b = 0.313 \pm 0.013$, $\eta = \alpha_3(M_Z)/\alpha_3(m_b) = 0.548$, $I(z) = 1 - 8z^2 + 8z^6 - z^8 - 24z^4 \ln z$ is a phase space factor for the $b \rightarrow ce\bar{\nu}_e$ decay, and the denominator bracket ($f(z) \cong 2.41$) is a QCD correction to $b \rightarrow ce\bar{\nu}_e$. In LO, $C_7^{eff}(m_b)$ is given by^{2,3}

$$C_7^{eff}(m_b) = \eta^{\frac{16}{23}} C_7(M_W) + \frac{8}{3} (\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}) C_8(M_W) + C_2(M_W) \quad (5)$$

where C_2 represents the operator mixing with the 4-quark operators.

The advantage of using the ratio R is that poorly known CKM matrix elements and a $(m_b)^5$ factor cancel out and one is left with the relatively well known ratios $|V_{ts}^*V_{tb}/V_{cb}|^2 = 0.95 \pm 0.04$ and $z = m_c/m_b$. There remain, however, a number of errors and uncertainties in the above results which we now list:

- (i) Existing errors in the input parameters $\alpha_3(M_Z) = 0.12 \pm 0.01$; z ; $BR(B \rightarrow X_c e \bar{\nu}_e)$; and the CKM matrix element ratio.
- (ii) Use of spectator model. [Corrections are of $O(1/m_b^2)$].
- (iii) Neglect of the next to leading order (NLO) corrections. This is the largest error since QCD corrections to this process are large.

An estimate of the size of the NLO corrections can be obtained by finding the change in the LO result between running the RGE to $\mu = m_b/2$ and $\mu = 2m_b$. Thus when higher order corrections are included, the μ dependence should disappear, and so the μ dependence of the LO gives a measure of the size of the NLO corrections. The neglect of the NLO corrections is then estimated to cause an error of about⁴ $\pm 25\%$.

Combining the above errors in quadrature, the LO calculation yield for the Standard Model for $m_t = 174$ GeV the result^{4,5}

$$BR[B \rightarrow X_s \gamma] \cong (2.9 \pm 0.8) \times 10^{-4} \quad (6)$$

which is about a 30% error. Comparing Eqs. (1) and (6), we see at this point that it is not possible to distinguish between the Standard Model being in agreement with experiment or differing from it by a factor of 2. Some of the NLO corrections have

now been calculated^{5,6}, but a clear answer requires a full calculation of the NLO corrections which is not easy (as they involve calculating the finite parts of two loop and divergent parts of three loop diagrams).

There is an additional theoretical correction due to the existence of heavy thresholds. (This is really part of the NLO corrections but requires special treatment.) The LO analysis considers the effective theory at $\mu = M_W$ and integrates the RGE down to $\mu \approx m_b$. However, other particles in the loop are not degenerate with W boson, and one really should start at a higher mass scale and integrate out each particle as one crosses its mass threshold. For the Standard Model W-top graph, this leads to about a 15% enhancement^{7,8}. For the SUSY case, it is estimated⁸ that the effect is small for the H-top loop, and perhaps $\pm 15\%$ for the $\tilde{W} - \tilde{t}$ loop. These effects depend on the mass spectrum of the SUSY particles, and thus may be important as SUSY diagrams in $b \rightarrow s + \gamma$ decay can occur with opposite sign to the Standard Model one.

3. Minimal Supergravity Model (MSGM)

In order to obtain the SUSY prediction for the $b \rightarrow s + \gamma$ branching ratio, one needs to specify the SUSY particle masses. The MSSM is not very useful in this respect as it depends on too many (about 20) arbitrary parameters. We will here make use of the minimal supergravity model⁹ (MSGM) which has much greater predictive power.

The MSGM has already exhibited a number of accomplishments, and has made a number of predictions which can be tested in forthcoming experiments. We list some of these here:

- The MSGM accounts for the unification of couplings at the GUT scale $M_G \approx 10^{16}$ GeV implied by the LEP data¹⁰
- It allows for spontaneous breaking supersymmetry in the “hidden” sector (which cannot be achieved in a phenomenologically satisfactory way in the MSSM).
- Flavor changing neutral interactions are naturally suppressed.
- The masses of the 32 new SUSY particles and all their interactions are predicted in terms of only four parameters [m_o , the universal scalar mass; $m_{1/2}$, the universal gaugino mass; A_o , the universal cubic soft breaking parameter; $\tan\beta \equiv \langle H_2 \rangle / \langle H_1 \rangle$] and the sign of μ , the Higgs mixing parameter. [Here (H_1, H_2) are the Higgs that gives rise to (down, up) quark masses.] Thus the theory makes many predictions that can be tested at⁹ LEP2 and the LHC and at an upgraded Tevatron¹¹.

- Models with R parity yield a natural candidate for cold dark matter, the lightest neutralino \tilde{Z}_1 , with relic abundances consistent with COBE and other astrophysical data.
- If representations breaking the GUT group are not large, the Gut threshold corrections are small, and hence low energy predictions are mostly independent of the choice of Gut group.
- The spontaneous breaking of supersymmetry at M_G naturally triggers the breaking of $SU(2) \times U(1)$ at the electroweak scale by radiative breaking. Thus the MSGM offers a natural explanation of electroweak breaking.
- For models with proton decay, the decay rate is suppressed by a factor of $\approx 10^4$ relative to Standard Model Guts, and hence is consistent with current data. (However, such models generally predict rates that should be detectable in the next round of p-decay experiments.)

It is convenient, in the following discussion to trade $m_{1/2}$ and A_o for the two low energy parameters, $m_{\tilde{g}}$ (the gluino mass) and A_t (the t-quark A parameter at the electroweak scale). We then explore the entire parameter space over the range

$$100\text{GeV} \leq m_o, m_{\tilde{g}} \leq 1\text{TeV}; \quad -6 \leq A_t/m_o \leq 6; \quad \tan\beta \leq 20 \quad (7)$$

subject to the constraints that there be no violation of the LEP and Tevatron bounds on SUSY masses, and that radiative breaking of $SU(2) \times U(1)$ occurs. We chose a mesh with $\Delta m_o = 100\text{GeV}$, $\Delta m_{\tilde{g}} = 25\text{GeV}$, $\Delta A_t = 0.5$, $\Delta(\tan\beta) = 2, 4$. One then determines the masses and couplings of the SUSY particles for each of the parameter points, which allows calculation of the $b \rightarrow s + \gamma$ rate in the LO approximation.

4. Parameter Dependence

The dominant contributions to the $b \rightarrow s + \gamma$ loops come from the third generation quarks and squarks. The $\tilde{W} - \tilde{t}$ loops play an important role as the two stop states, \tilde{t}_1 and \tilde{t}_2 ($m_{\tilde{t}_1} < m_{\tilde{t}_2}$) are very split. The stop mass matrix reads

$$\begin{pmatrix} m_{\tilde{t}_L}^2 & m_t(A_t m_o + \mu c t n \beta) \\ m_t(A_t m_o + \mu c t n \beta) & m_{\tilde{t}_R}^2 \end{pmatrix} \quad (8)$$

Because m_t is large, the \tilde{t}_1 can become light, and in fact large regions of the parameter space get excluded when \tilde{t}_1 is driven tachyonic.

As is well known¹², the $H^- - t$ loop adds constructively to the Standard Model to increase the $b \rightarrow s + \gamma$ branching ratio. However, the $\tilde{W} - \tilde{t}$ loop can enter with either sign increasing or decreasing the total amplitude, as is seen in Fig. 2. Note

that the effect of the $\tilde{W} - \tilde{t}_1$ graph is larger for light \tilde{t}_1 , as one might expect, and in the MSGM there exist parameter points where the total branching ratio can be below or above the Standard Model result.

Solving for the eigenvalues of Eq. (7) shows that $m_{\tilde{t}_1}^2$ is smaller if A_t and μ have the same sign or when $m_{\tilde{t}_R}^2$ is negative. The latter can happen if $A_t < 0$. These effects can be seen in Figs. (3-5)^{13,14}. Fig. 3 shows that the branching ratio is largest when

Fig. 2 Scatter plot for LO BR($b \rightarrow s + \gamma$) as a function of $m_{\tilde{t}_1}$.

when m_o and $m_{\tilde{g}}$ are small ($m_{\tilde{W}_1} \simeq (\frac{1}{3} - \frac{1}{4})m_{\tilde{g}}$) and that it is larger when A_t and μ

Fig. 3 $BR(b \rightarrow s + \gamma)$ vs. $m_{\tilde{W}_1}$, $m_t = 165$ GeV, $\tan\beta=5$, $|A_t/m_o|=0.5$, $\alpha_G^{-1}=24.11$.

Graphs (a) and (b) are for $A_t < 0$, (c) and (d) for $A_t > 0$. Graphs (a) and (c) are for $\mu > 0$ and (b) and (d) are for $\mu < 0$.

have the same sign then when they have opposite signs (as one would expect since $m_{\tilde{t}_1}$ is then smaller). The gaps in the graphs (a) and (b) occur due to the fact that the $m_{\tilde{t}_1}$ has turned tachyonic (which can occur when A_t is negative). Fig. 4 shows that the branching ratio increases as m_t increases (since $m_{\tilde{t}_1}$ shrinks when the off

Fig. 4 Same as Fig. 3 for $m_t = 170$ GeV

diagonal elements Eq. (7) grow) and in fact for $A_t < 0$ the region for tachyonic $m_{\tilde{t}_1}$ has grown. Note that the $A_t > 0$ curves are only slightly dependent on m_t .

Fig. 5 shows the sensitivity of the branching ratio to α_G . For $A_t < 0$ a larger portion of the parameter space is excluded because \tilde{t}_1 is driven tachyonic when α_G

Fig. 5 Same as Fig. 3 with $\alpha_G^{-1} = 24.5$

decreases (because h_t , the t Yukawa coupling constant, is driven closer to its Landau pole. (Again, for $A_t > 0$, there is little effect due to this small change in α_G .) If one increases both m_t and α_G^{-1} , the effects combine to eliminate the $A_t < 0$ part of the parameter space for $m_o > 100$ GeV for this case.

5. $b \rightarrow s + \gamma$ Constraints on Dark Matter Detection

The experimental results on $b \rightarrow s + \gamma$ can impose constraints on dark matter analyses¹⁵. We saw in Sec. 4, that when μ and A_t have the same sign, the $b \rightarrow s + \gamma$ decay rate is larger than when μ and A_t have opposite signs¹³. This increase is particularly marked when m_o and $m_{\tilde{g}}$ are small. This is also the region of largest dark matter detection rates. Thus one expects that for such type situations, the experimental $b \rightarrow s + \gamma$ rate of Eq. (1) might already be able to rule out some of the SUSY parameter space where the dark matter detection rates are expected to be highest and hence most accessible experimentally.

To examine this in more detail, we consider the experimental branching ratio $BR(b \rightarrow s + \gamma) = 2.32 \pm 0.66 \times 10^{-4}$ and ask, what part of the dark matter detection rates correspond to parameter points where the $b \rightarrow s + \gamma$ theoretical rate is within the 95% CL of the experimental value. We use here the LO calculation of the $b \rightarrow s + \gamma$ rate as a figure of merit¹⁶. Fig. 6 shows the maximum and minimum event rates for a Pb dark matter detector as a function of A_t for $\mu < 0$. The cosmological con-

Fig. 6 The maximum and minimum detection rates for a Pb dark matter detector as a function of A_t for $\mu < 0$. The solid curve is without the $b \rightarrow s + \gamma$ constraint while the dot-dash curve imposes the constraint that the theoretical LO branching ratio be within the 95% CL of the experimental value.

straints on the relic density require that the allowed parameter space be mainly for $A_t > 0$. Thus for $\mu < 0$, the predicted $b \rightarrow s + \gamma$ rate is large only in the small region where $A_t < 0$, and it is only in this region where the experimental value of the $b \rightarrow s + \gamma$ branching ratio eliminates a significant part of the parameter space. Note that the minimum event rates are unaffected.

Fig. 7 shows the corresponding graphs for $\mu > 0$. Here the majority of parameter

Fig. 7 Same as Fig. 6 for $\mu > 0$.

space occurs for A_t and μ having the same sign, and hence the theoretical LO $b \rightarrow s + \gamma$ decay rate is larger than the experimental rate over most of the parameter space. In fact, the 95% CL bound eliminates all of the parameter space except in the band $-0.5 \leq A_t/m_o \leq 0.5$.

6. $b \rightarrow s + \gamma$ Decay Constraints on Proton Decay

We consider next supergravity Gut models that allow for proton decay, and restrict the discussion to SU(5)-type models where proton decay is mediated by a superheavy

Fig. 8 Example of SUSY proton decay diagrams where the baryon and lepton number violations occur at the color triplet \tilde{H}_3 vertices.

Higgsino color triplet \tilde{H}_3 with mass $M_{H_3} = O(M_G)$. The basic diagram is shown in Fig. 8 where the chargino \tilde{W} exchange “clothes” the Higgsino interactions. The decay rate can be written in the form $\Gamma(p \rightarrow \bar{\nu} K^+) = \text{const} |B|^2 / M_{H_3}^2$ where B represents the clothing loop amplitude. The current experimental bound on the proton lifetime is¹⁷ $\tau(p \rightarrow \bar{\nu} K^+) > 1 \times 10^{32}$ yr which places a bound on B of¹⁸

$$|B| \lesssim 100 \left(\frac{M_{H_3}}{M_G} \right) \text{GeV}^{-1}; \quad M_G \equiv 2 \times 10^{16} \text{GeV} \quad (9)$$

In the following we limit M_{H_3} to obey $M_{H_3} \leq 10M_G$, so that there not be unknown Planck scale physics entering into the analysis.

We examine here those parts of the parameter space that simultaneously satisfies the proton decay lifetime bound and the cosmological bound that the \tilde{Z}_1 be the cold component of dark matter, i.e.¹⁹ $0.10 \lesssim \Omega_{\tilde{Z}_1} h^2 \lesssim 0.35$ where $\Omega_{\tilde{Z}_1} = \rho_{\tilde{Z}_1} / \rho_c$ and $h = H / (100 \text{ km/sec Mpc})$. Here $\rho_{\tilde{Z}_1}$ is the relic mass density of the \tilde{Z}_1 , ρ_c is the critical mass density that closes the Universe, and H is the Hubble constant. We then ask what fraction of the parameter points satisfying both the proton decay bound and the cosmological constraints are consistent with the CLEO measurement of the $b \rightarrow s + \gamma$ decay rate. Using the leading order (LO) predictions for the $b \rightarrow s + \gamma$ decay rate, we find that 95% of the parameter points that satisfy both the proton lifetime and cosmological bounds lie within the 95% CL bounds of the CLEO data. (13% lie within 68% CL bounds of the CLEO data). The parameter points satisfying the proton decay bound generally give a value of $\text{BR}(b \rightarrow s + \gamma)$ which lies above the central CLEO value. However, a number of the NLO corrections⁵ do decrease the theoretical value. Thus the $b \rightarrow s + \gamma$ decay does not as yet seriously constrain proton decay models. We note that the parameter points satisfying the proton decay, cosmological and $b \rightarrow s + \gamma$ decay bounds require

$$m_{\tilde{g}} < 375 \text{GeV}; \quad m_o > 400 \text{GeV}; \quad 0 \leq A_t / m_o \leq 0.5; \quad \tan\beta \leq 10 \quad (10)$$

Because the proton decay bound requires $\tan\beta$ to be small the dark matter event rates will remain small, i.e.

$$R < 0.01 \text{event/kg da} \quad (11)$$

Thus if proton decay were seen at the next round of proton decay experiments (e.g. at Super Kamiokande) these models would predict that \tilde{Z}_1 dark matter would not be observable with current dark matter detectors.

7. Conclusions and Summary

The $b \rightarrow s + \gamma$ decay is a process which is sensitive to new physics and thus is an excellent place to test models of new physics. However, both theory and experiment need improvement if quantitative tests are to be made. Using the leading order (LO) approximation to the theory, a number of semi-quantitative results do exist:

The rate for $b \rightarrow s + \gamma$ is largest when both m_o and $m_{\tilde{g}}$ are small and when μ and A_t have the same sign. Thus these are the parts of the parameter space which will get eliminated if the experimental value of the branching ratio stays below the Standard Model number.

Large parts of the parameter space for $A_t < 0$ gets deleted when m_t and α_G^{-1} increases, as the \tilde{t}_1 squark turns tachyonic. This is a consequence of m_t being large.

The current $b \rightarrow s + \gamma$ experimental bound appears to eliminate most of the parameter space which is consistent with the \tilde{Z}_1 as cold dark matter for $\mu > 0$, but does not effect the $\mu < 0$ part very much.

Most of the parameter points which satisfy both current proton decay bounds and \tilde{Z}_1 relic density bounds, are also consistent with present $b \rightarrow s + \gamma$ experimental rates. However, as the data improves, the $b \rightarrow s + \gamma$ decay will make significant impact on models that predict proton decay.

One may expect significant constraints on new physics models once the data and theoretical predictions on the $b \rightarrow s + \gamma$ decay become more accurate.

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